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NUCLEAR SPIN POLARIZATION OF HYDROGEN BY COLLISION WITH OPTICALLY PUMPED SODIUM

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ABSTRACT

Theoretical calculations have been carried out which results show that the spin-exchange collision in the low magnetic field between laser oriented sodium and hydrogen can be used to produce nuclear spin polarized hydrogen directly. It is shown that after making $\sim$8 collisions, more than 90% nuclear spin polarization could be expectable. Nuclear spin polarization decreases as the applied magnetic field increases. On the contrary, electron spin polalization of hydrogen increases with the magnetic field.

1. Introduction

It is no exaggeration to mention that in low and medium energy nuclear physics, the experimental data taken with unpolarized particles are only useful for complementary to those taken with polarized particles. In order to clarify the nuclear reaction mechanism and nuclear structure, a wide variety of the polarized projectiles and targets with high polarization and intensity are indispensable. There exist, however, no single polarized source and target which can satisfy such a wide range of requirements. Therefore, "the right sources (or targets) for the right experiments" philosophy has been observed. So far, several polarization schemes have been proposed and some are brought into routine operation.

The polarized ion sources based on the optical pumping method may open a new horizon for a universal polarized ion source. High polarization and intensity of a wide variety of polarized projectiles may become available with rather low power laser. In the present paper we will present some preliminary results of theoretical calculations on the obtainable nuclear spin polarization of hydrogen by collision with the optically oriented sodium directly in the low magnetic field.

2. Method of Calculations and Results

Knize et al.[1] have shown that laser optical pumping spin-exchange between Rb and hydrogen atoms seems to be an efficient way of producing of large amount of nuclear spin polarized hydrogen with moderate laser power ($\sim$1 watt).

We have calculated obtainable hydrogen nuclear polarization by spin-exchange with optically orientated sodium ($Na(\uparrow) + H(\downarrow) \rightarrow Na(\downarrow) + H(\uparrow)$). For the sake of simplification of the calculations, we assumed only one substate ($F = 2$ and $m_F = +2$) of sodium 8 hyperfine structures is completely populated by optical pumping.

Occupation probability of hydrogen substate n (j = 1,2,3 and 4) after the k collision can be gien by following equation

$$n_j^k = \sum_{i=1}^{4} \sum_{\ell=1}^{8} \sum_{m=1}^{8} n_j^{k-1} N_\ell^{k-1} |< j,m | P_0 + e^{-i\phi_{st}} P_1 | i,\ell >|^2$$

where i and j; hydrogen substates before and after the collision (i,j = 1~4),
ℓ and m; sodium substates before and after the collision (ℓ,m = 1~4),
P_0 and P_1 ; the projection operators for total spin angular momentum 0 and 1, respectively.
ϕ_{st} ; relative phase between singlet and triplet parts of the wave function after the collision,
n_i^{k-1} and N_ℓ^{k-1}; occupation probabilities after $(k-1)^{th}$ collision for hydrogen and sodium, respectively.

Table 1 shows the obtained results of the square of the matrix elements avaraged over ϕ_{st}. Table 2 shows the results expressing the occupation probabilities of four hydrogen substates after k^{th} collision n_j^k(j = 1~4).

Table 1. Square of the matrix elements averaged over relative phase.

j,m \ i,ℓ	(1,1)	(1,2)	(1,3)	(1,4)	(1,5)	(1,6)	(1,7)	(1,8)	(2,1)	(2,2)	(2,3)	(2,4)	(2,5)	(2,6)	(2,7)	(2,8)	(3,1)	(3,2)	(3,3)	(3,4)	(3,5)	(3,6)	(3,7)	(3,8)	(4,1)	(4,2)	(4,3)	(4,4)	(4,5)	(4,6)	(4,7)	(4,8)
(1,1)	1																															
(1,2)		25/32						3/32	1/16																1/16							
(1,3)			5/8				1/8			3/32						1/32										3/32						
(1,4)				11/32		3/32					3/32				3/32												3/32					
(1,5)					1/2							1/16		3/16														1/16				
(1,6)				3/32		25/32					1/32				1/32												1/32					
(1,7)			1/8				5/8			3/32						1/32										3/32						
(1,8)		3/32						17/32	3/16																3/16							
(2,1)		1/16						3/16	5/8																1/8							
(2,2)			3/32				3/32			5/8							1/16									1/32						3/32
(2,3)				3/32		1/32					5/8							3/32						1/32							1/8	
(2,4)					1/16							5/8							3/32				3/32							3/32		
(2,5)													5/8							1/16		3/4							1/8			
(2,6)					3/16									5/8					1/32				1/32					3/32				
(2,7)				3/32		1/32									5/8			3/32						1/32			1/8					
(2,8)			1/32				1/32									5/8	3/16									3/32						1/32
(3,1)										1/16						3/16	1/2									1/16						3/16
(3,2)											3/32				3/32			17/32						3/32			3/32				3/32	
(3,3)												3/32		1/32					5/8				1/8					3/32		1/32		
(3,4)													1/16							25/32		3/32							1/16			
(3,5)																					1											
(3,6)													3/16							3/32		17/32										
(3,7)												3/32		1/32					1/8				5/8									
(3,8)											1/32				1/32			3/32						25/32								
(4,1)		1/16						3/16	1/8																5/8							
(4,2)			3/32				3/32			1/32						3/32	1/16									5/8						
(4,3)				3/32		1/32									1/8			3/32						1/32			5/8					
(4,4)					1/16							1/32		3/32					3/32				3/32					5/8				
(4,5)													1/8							1/16		3/16							5/8			
(4,6)					3/16							3/32		1/32					1/32				1/32							5/8		
(4,7)				3/32		1/32					1/8							3/32						1/32							5/8	
(4,8)			1/32				1/32			3/32						1/32	3/16															5/8

Table 2. Occupation probabilities of hydrogen substates after k^{th} collision.

j	F	m_F	n_j^k
1	1	1	$(n_1^{k-1} + \frac{1}{4} n_2^{k-1} + \frac{1}{4} n_4^{k-1}) \times N_1^{k-1}$
2	1	0	$(\frac{5}{8} n_2^{k-1} + \frac{1}{4} n_2^{k-1} + \frac{1}{8} n_4^{k-1}) \times N_1^{k-1}$
3	1	-1	$\frac{1}{2} n_3^{k-1} \times N_1^{k-1}$
4	0	0	$(\frac{1}{8} n_2^{k-1} + \frac{1}{4} n_3^{k-1} + \frac{5}{8} n_4^{k-1}) \times N_1^{k-1}$

From these results, the degree of nuclear spin polarization can be obtained and is shown in Fig.1 as a function of the number of collisions assuming N_1 = 1. As can be seen from this figure, nuclear polarization increases as the result of successive collision with optically oriented sodium.

Fig.2 shows another interesting results obtained from the present calculations. Nuclear spin polarization of hydrogen becomes almost zero as the applied magnetic field increases. On the contrary, the electron polarization of hydrogen approaches more than 90% after several collisions with sodium as the applied external magnetic field is increased.

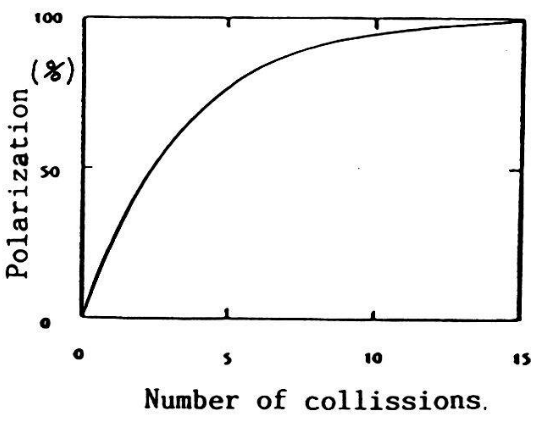

Fig.1 Nuclear spin polarization as a function of the number of collisions.

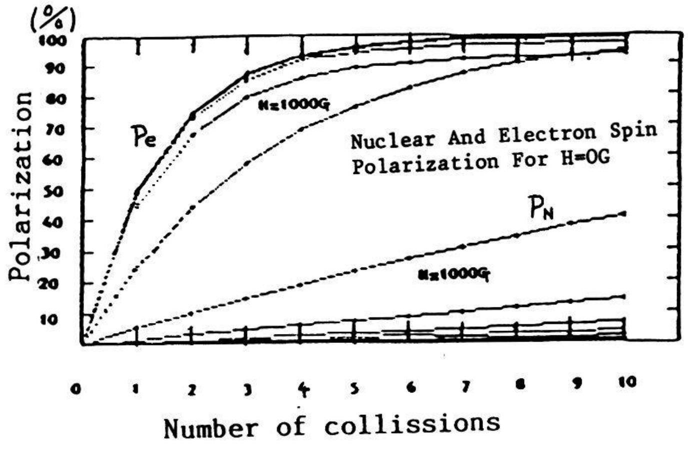

Fig.2 Nuclear spin and electron spin polarization of hydrogen atom as a function of the magnetic field. P_N; nuclear spin polarization and P_e ; electron spin polarization.

3. Summary

In conclusion, we can expect very high nuclear spin polarization directly through the spin-exchange collision if the time between spin-exchange collision is short compared to either the spin lattice relaxation time or the pumping time for the system. Furthermore, owing to the high spin-exchange cross section, we will be able to obtain highly intense nuclear spin polarized hydrogen by using relatively low power laser.

References

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